Impact of Rubber Tire Chips on Clayey Soil Rigid Payment Design: A Sustainable Approach

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Abstract. This study explores the benefits of incorporating recycled rubber tire chips into clayey soil for sustainable rigid pavement design. While previous research has examined the impact of rubber tire chips on bearing capacity and modulus of subgrade reaction, no work has been done to relate such information to the thickness of rigid pavements. The addition of rubber tire chips enhanced bearing capacity and subgrade reaction, reducing pavement thickness and substantial cost savings. Notably, the mixture with RTC 0.25" and 0.5% content demonstrates a 50.11% increase in Net Allowable Bearing Capacity (ΔNABC) and the highest reduction in thickness (Δ Thickness) by -2.40%, emphasizing its potential for practical application in sustainable rigid pavement design. This research advocates for the practical and eco-friendly use of rubber tire chips in clayey soil, addressing waste tire accumulation and improving pavement performance. Engineers can leverage these findings to enhance pavement performance while minimizing construction costs. Future research could assess the long-term durability of this sustainable solution.

Keywords: Rubber Tire Chips, Rigid Pavement, Bearing Capacity, Modulus of subgrade reaction

1. Introduction

The construction of rigid pavements is an essential component of modern transportation infrastructure. Rigid pavements are designed to withstand heavy traffic loads and provide vehicles with a durable, long-lasting surface. However, the construction and maintenance of rigid pavements can be expensive, and there is a constant search for new and innovative ways to improve their design and reduce costs. One area of interest is using waste materials as an additive in pavement construction. One such material is rubber tire chips obtained from discarded tires. Rubber tire chips have been shown to improve the properties of pavement materials, such as increasing the strength and durability of the pavement, reducing the noise level, and enhancing the pavement's resistance to cracking.

Rubber tire chips have demonstrated potential in improving pavement properties, including increased strength, enhanced durability, noise reduction, and resistance to cracking. However, the effects can vary when added to clayey soil, presenting advantages and drawbacks. The potential benefits are improved drainage, enhanced aeration, reduced soil compaction, temperature regulation, erosion control, and the environmentally friendly use of recycled materials. Conversely, considerations include long-term degradation, aesthetic concerns, contaminants, and adherence to local regulations. Rubber tire chips, ranging from 12 to 50 mm in size, are recycled pieces of shredded tires widely utilized in landscaping, playgrounds, and road construction. These chips exhibit excellent elasticity, providing resilience to absorb shocks and impacts, reducing the risk of surface damage. Their thermal insulation properties, resistance to water, chemicals, and UV radiation, coupled with durability under heavy loads, make them an ideal material for various applications, particularly in road construction. The versatility of rubber tire chips is underscored by their use in different categories, including tire shreds (50-305 mm) and granulated rubber (≤ 12 mm), as outlined in Table 1 below.

Table 1: Forms of tire waste

S. No.	Tire Category	Size (mm)
1.	Scrap Tire	-
2.	Tire Shreds	50-305
3.	Tire Chips	12-50
4.	Granulated Rubber	≤ 12

Numerous studies have delved into the impact of incorporating rubber tire chips into clayey soil for diverse engineering applications. For instance, Singh et al. (2017) investigated shredded rubber tire as a soil stabilizer, exploring various percentages in clayey soil and scrutinizing resultant changes in soil properties [1]. Kumar et al. (2020) explored the combination of shredded tire and lime for clayey soil stabilization, determining optimal proportions for enhanced strength [2]. Reddy et al. (2016) examined shredded rubber's use to enhance soil characteristics, revealing improvements in strength, compressibility, and permeability [3]. Singh (2016) focused on CBR value

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behavior, finding optimal shredded rubber tire content and size [4]. Sharma et al. (2015) observed the impact of tire chips on clayey soil geotechnical properties, revealing optimal percentages for CBR improvement [5]. Tiwari et al. (2014) explored shredded rubber tires' geotechnical effects, showcasing improvements in shear strength and compressibility [6]. Zonberg et al. (2004) assessed tire shreds in embankment construction, highlighting successful performance in stability, settlement, and drainage [7]. Ayothiraman et al. (2011) used shredded waste tire chips for subgrade soil stabilization, indicating significant improvements in CBR and maximum dry density [8]. Alafeena et al. (2020) studied grouting effects on sandy soil, emphasizing substantial improvements in the modulus of subgrade reaction [9]. Ravichandran et al. (2016) examined waste tire crumb rubber's role in stabilizing weak soils, reporting positive effects on strength, compressibility, and permeability [10]. Sitiadji et al. (2010) proposed a method for estimating the modulus of subgrade reaction using CBR test data, providing a simpler alternative for pavement design [11]. Ratnam et al. (2016) explored waste tire rubber chips' impact on soil strength and settlement, noting improvements with careful consideration of factors [12]. Hambirao et al. (2014) investigated shredded rubber tire chips for soil stabilization, presenting engineering property improvements and a substantial reduction in pavement thickness [13]. Tabrizi et al. (2019) simulated soil-rubber tire behavior, revealing enhanced shear strength and deformation characteristics, advocating for sustainable soil stabilization [14]. Liu et al. (2020) conducted a comprehensive review of recycled tire-sand/soil, highlighting their potential as geotechnical alternatives with environmental benefits [15]. Akbarimehr et al. (2021) explored waste rubber's effect on Tehran clay, suggesting its potential to improve strength behavior with environmental advantages [16]. Bosscher et al. (1997) investigated tire chips for embankments, proposing a design method and emphasizing their suitability and sustainability [17]. Edil et al. (1994) explored tire chips in soil mixtures, revealing improved compressive strength and permeability while discussing potential applications and environmental considerations [18]. Edeskär et al. (2003) discussed tire shreds in road construction, emphasizing their lightweight and frost insulation properties with potential environmental benefits [19]. Ghazavi (2005) optimized tire shreds for sand stabilization, showcasing improved shear strength parameters and suggesting a sustainable approach to waste tire disposal [20].

In the present investigation, an attempt is made to stabilize clayey soil and design rigid pavement accordingly. Clayey soil was collected from a local site in District Nowshera. Index and engineering properties of soil were estimated using standard ASTM procedures. Unconfined compression Tests, Direct Shear Tests, and California Bearing Ratio Tests were performed on the soil and soil-tire chips mixtures. The bearing capacity and modulus of the subgrade reaction of the soil-tire chips mixture were estimated using Terzaghi's bearing capacity equation and Bowles correlation, respectively. The Ks values were used to design the rigid pavement using the AASHTO 1993 Procedure.

2. Materials

2.1 Clayey Soil

The research utilizes high clay-content soil obtained from Nowshera. Classified as CH (clay with high plasticity) based on inherent characteristics, the soil undergoes standard laboratory tests, encompassing sieve analysis, Atterberg limits, specific gravity, moisture content, and other pertinent parameters for comprehensive characterization.

2.2 Rubber Tire Chips

The study employed recycled rubber tire chips sourced from a local recycling plant. The chips underwent cleaning and precision cutting into uniform square sizes (0.25", 0.375", 0.5"). Bulk density and specific gravity tests were conducted to ensure quality, adhering to ASTM standards for accurate characterization. Various sized tire rubber chips used in this study are given in Figure 3.1.

Fig. 2.1 Various sized tire chips

3. Methodology

This study investigated the potential of using tire chips as an additive to improve soil properties for pavement applications. The study was conducted in three phases: material characterization, strength testing, and pavement design analysis.

3.1 Material Characterization

During the material characterization phase, various tests were conducted to determine the properties of soil and tire chips. The sieve analysis method assessed the grain size distribution as per ASTM D422 [21]. The Atterberg limits, including the liquid and plastic limits of the soil, were determined using the cone penetration method specified in ASTM D4318 [22]. Specific gravity for both materials was measured using the pycnometer method described in ASTM D854 [23]. Moisture content was evaluated through the oven drying method outlined in ASTM D2216 [24], while bulk density was determined using the sand cone method as per ASTM D2937 [25]. Lastly, the modified Proctor compaction curve for soil and tire chip mixtures was established following ASTM D1557 [26]. These tests provided essential insights into the material properties critical for further analysis.

3.2 Mixing Rubber Tire Chips with Clayey Soil

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A representative sample of clayey soil was collected from District Nowshera, KPK Province of Pakistan, and spread evenly on a clean, dry surface to allow for complete air drying. The dried soil was then gently broken up to ensure uniform drying. Rubber tire chips of the desired sizes (0.25 inches, 0.375 inches, and 0.5 inches) were thoroughly washed with clean water to remove any dirt or debris and were subsequently dried completely. The addition of tire chips in the soil sample are given in Figure 3.1.

Fig. 3.1 Mixing tire rubber chips in soil

Three sets of mixing containers were prepared for each rubber tire chip size, each clearly labeled with the corresponding size and mixing ratio (5%, 10%, or 15%). The required amounts of dried clayey soil and rubber tire chips were carefully measured and mixed thoroughly in each container until a uniform distribution was achieved. The clayey soil's optimum moisture content (OMC) was determined using the Modified Proctor compaction test ASTM D1557 [26]. Water was added or removed to the soil-rubber chip mixtures as needed to achieve the determined OMC, and the mixtures were mixed thoroughly to ensure even moisture distribution. The prepared soil-rubber chip mixtures were then transferred into appropriate testing molds or containers, compacted according to the specific test requirements, and clearly labeled with the rubber tire chip size and mixing ratio. The prepared samples were stored in a controlled environment until testing to maintain consistent temperature and humidity conditions and prevent any changes in sample properties.

3.3 Strength Testing

During the strength testing phase, various tests were conducted to evaluate the strength properties of soil and tire chip mixtures. The unconfined compressive strength was measured using the standardized method outlined in ASTM D2166 [27]. The direct shear strength of the mixtures was assessed following the procedure specified in ASTM D3080 [28]. Additionally, the California Bearing Ratio (CBR) of the soil and tire chip mixtures was determined in accordance with the guidelines provided in ASTM D1883 [29]. These tests were essential in understanding the strength characteristics of the materials for further analysis.

3.4 Pavement Design Analysis

The pavement design analysis phase employed the AASHTO 1993 design guide to develop a rigid pavement incorporating soil and tire chip mixtures. This comprehensive design process meticulously considered critical factors influencing pavement performance, including reliability, PCC elastic modulus, slab thickness, drainage coefficient, load transfer coefficient (J Factor), and modulus of subgrade reaction (k). The AASHTO 1993 design guide was the foundation for designing a rigid pavement utilizing soil and tire chip mixtures as a sustainable alternative to conventional pavement materials. The design process rigorously evaluated various parameters that affect pavement performance, ensuring the development of a durable and reliable pavement structure.

4. Testing Program

4.1 Unconfined Compressive Strength Test

The UCS test was performed on soil samples alone and soil-tire chip mixtures with varying tire chip sizes (0.25 inches, 0.375 inches, and 0.5 inches) and percentages (5%, 10%, and 15%). A total of 10 UCS tests were conducted. The UCS test was conducted in accordance with ASTM D2166 [27]. The UCS test measures the unconfined compressive strength of a soil sample, which is the maximum force that can be applied to a cylindrical soil sample without causing it to fail. The UCS test is typically used to assess the strength of cohesive soils, such as clays.

4.2 Direct Shear Test

The Direct Shear test was performed on soil samples alone and soil-tire chip mixtures with varying tire chip sizes (0.25 inches, 0.375 inches, and 0.5 inches) and percentages (5%, 10%, and 15%). A total of 10 Direct Shear tests were conducted. Direct Shear test was conducted in accordance with ASTM D3080 [28]. The Direct Shear test determines the shear strength parameters of a soil sample, which are the cohesion and angle of internal friction. The shear strength parameters are important for understanding how soil will behave under different loading conditions, such as those encountered in pavements and slopes.

4.3 California Bearing Ratio Test

The CBR test was conducted on soil samples and soil-tire chip mixtures with varying tire chip sizes and percentages. A total of 10 CBR tests were conducted by varying tire chip sizes (0.25 inches, 0.375 inches, and 0.5 inches) and percentages (5%, 10%, and 15%). The CBR test was conducted in accordance with ASTM D1883 [29]. The CBR test is a standardized test used to evaluate the strength of soil and other materials for pavement applications. The CBR test measures the resistance of a soil sample to the penetration of a standard plunger. The CBR value is expressed as a percentage and is used to compare the strength of different soil materials.

5. Results and Discussions

A comprehensive testing program evaluated the mechanical behavior of soil mixed with tire chips of varying sizes (0.25, 0.375, and 0.5 inches) and percentages (5, 10, and 15%). The program included unconfined compression, direct shear, and California bearing ratio tests. Results were noted and compared as given below.

5.1 Unconfined Compressive Strength

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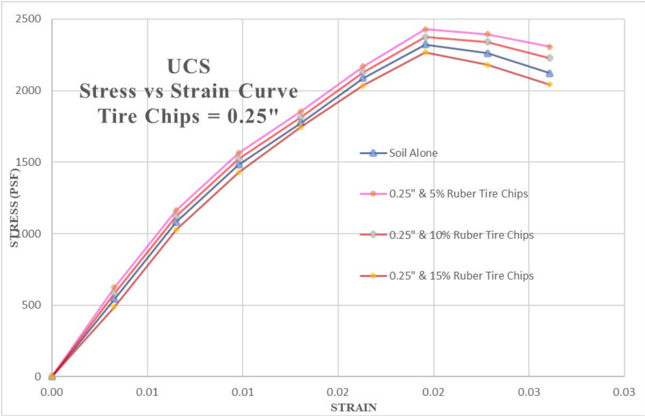

Fig 5.1 Stress-strain behavior of tire rubber chips (0.25”) modified soil mixtures

Figure 5.1 shows how soil acts when it's just soil and when mixed with 0.25" rubber tire chips at different amounts (5%, 10%, and 15%). It shows how the stress and strain change in these situations.

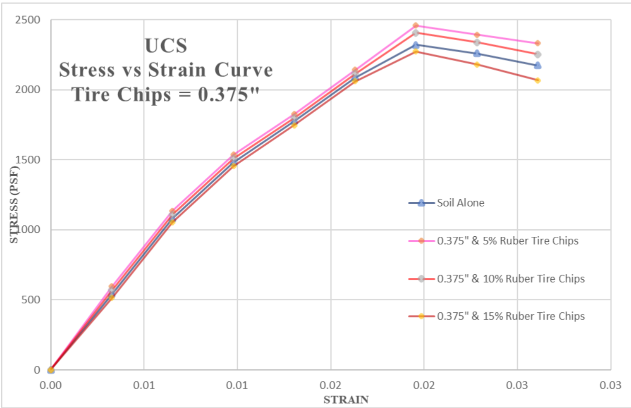

Fig 5.2 Stress-strain behavior of tire rubber chips (0.375”) modified soil mixtures

Figure 5.2 gives a picture of how soil acts when it's just soil and when mixed with 0.375" rubber tire chips at different amounts (5%, 10%, and 15%). It shows how the stress and strain change in these situations.

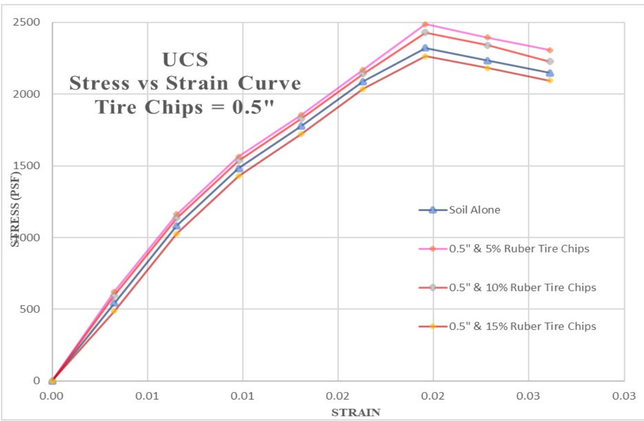

Fig 5.3 Stress-strain behavior of tire rubber chips (0.5”) modified soil mixtures

Figure 5.3 shows how soil acts when it's just soil and when mixed with 0.5" rubber tire chips at different amounts (5%, 10%, and 15%). It shows how the stress and strain change in these situations.

As it can be observed from the figures 5.1 to 5.3, the UCS value generally increases with an increasing tire chip percentage, up to a certain point. This is because the tire chips help to interlock the soil particles, increasing the soil mixture's strength. However, the tire chips start acting as voids, reducing the soil mixture's overall density and strength beyond a certain tire chip percentage.

The maximum UCS value is achieved with 0.5" tire chips at 5% tire chip percentage. This is likely because the 0.5" tire chips are the most significant size used in the study, providing the most interlocking effect. However, at higher tire chip percentages, the voids created by the tire chips start to outweigh the interlocking impact, and the UCS value decreases. These results suggest that tire chips can improve soil strength, but the tire chip size and percentage must be carefully chosen to maximize the benefit. For overall stability and strength increase, the 0.5" size at 5% appears to be the best mixture.

5.2 Shear Strength

The Direct Shear Test was performed to determine the shear strength parameters of the soil.

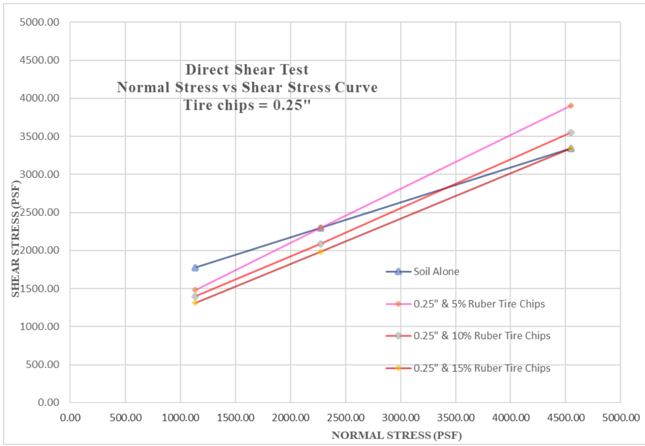

Fig 5.4 Normal vs shear stress behavior of soil tire chips (0.25”) mixtures

Figure 5.4 shows how soil behaves when it's just soil and when mixed with 0.25" rubber tire chips at different amounts (5%, 10%, and 15%). It shows how Normal stress and Shear stress change in these situations.

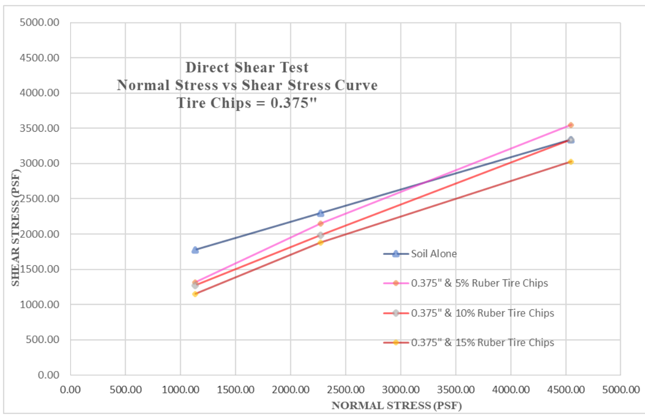

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Fig 5.5 Normal vs shear stress behavior of soil tire chips (0.375") mixtures

Figure 5.5 gives a picture of how soil acts when it's just soil and when mixed with 0.375" rubber tire chips at different amounts (5%, 10%, and 15%). It shows how Normal stress and Shear stress change in these situations.

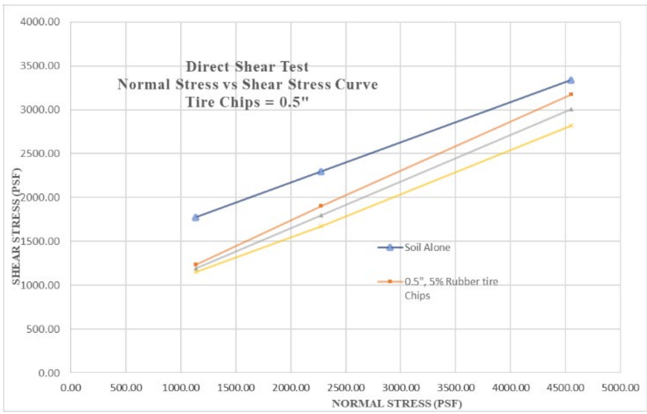

Fig 5.6 Normal vs shear stress behavior of soil tire chips (0.5") mixtures

Figure 5.6 shows how soil acts when it's just soil and when mixed with 0.5" rubber tire chips at different amounts (5%, 10%, and 15%). It shows how Normal stress and Shear stress change in these situations.

As it can be observed from the figures 5.4 to 5.6, the cohesion (C) of the soil mixture generally decreases with increasing tire chip size and percentage, while the friction angle (f) generally increases. This is likely because the tire chips act as voids in the soil mixture, reducing its overall density and cohesion. However, the tire chips also increase the surface roughness of the soil mixture, which increases the friction angle. The mixture with RTC 0.25" and 05% content shows the highest improvement in the angle of internal friction (Δ□□ by 40% and the lowest decrease in cohesion (ΔC) by -45.86% compared to the "Soil Alone" mixture. Therefore, the RTC 0.25" and 05% mixture appears to be the best combination for improving both the angle of internal friction and cohesion values.

5.3 CBR

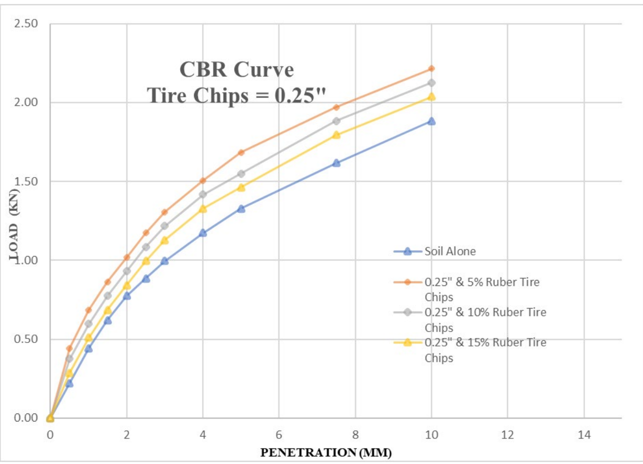

Fig 5.7 Variation of load penetration curve (RTC = 0.25")

Figure 5.7 gives a picture of how soil acts when it's just soil and when mixed with 0.25" rubber tire chips at different amounts (5%, 10%, and 15%). It shows the behavior of the Load Penetration curve.

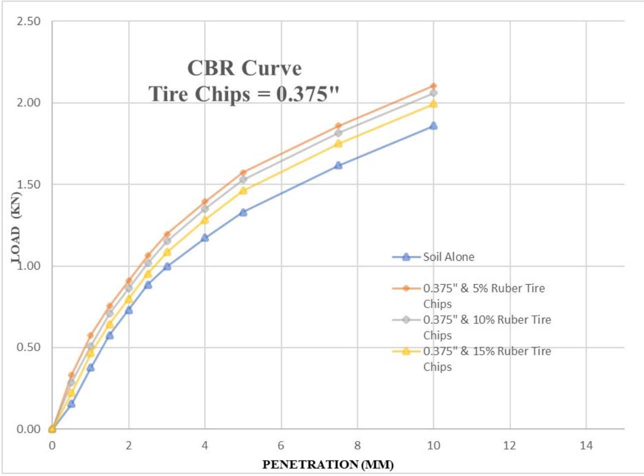

Fig 5.8 Variation of load penetration curve (RTC = 0.375")

Figure 5.8 gives a picture of how soil acts when it's just soil and when mixed with 0.375" rubber tire chips at different amounts (5%, 10%, and 15%). It shows the behavior of the Load Penetration curve.

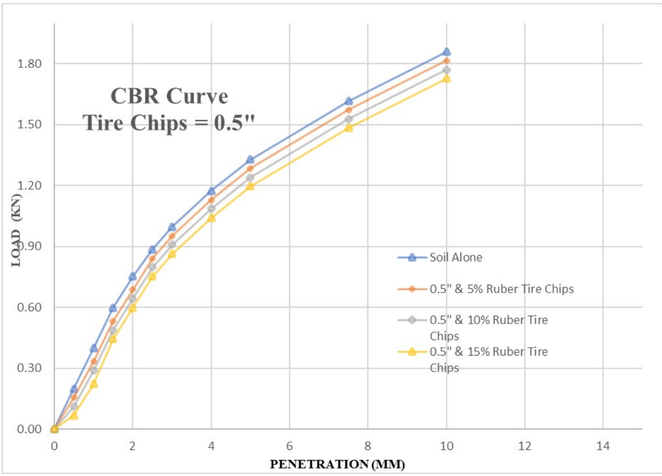

Fig 5.9 Variation of load penetration curve (RTC = 0.5")

Figure 5.9 shows how soil acts when it's just soil and when mixed with 0.5" rubber tire chips at different amounts (5%, 10%, and 15%). It shows the behavior of the Load Penetration curve.

As it can be observed from the figures 5.7 to 5.9 suggest that a thinner layer of RTC material with a lower mixing percentage tends to result in higher CBR values, indicating better soil strength. Conversely, thicker layers and higher mixing percentages may lead to lower CBR values, suggesting reduced soil strength. Tire chips of smaller size (0.25 inches) generally resulted in higher CBR Values than larger chips (0.375 and 0.5 inches). This is likely because smaller chips have a greater surface area-to-volume ratio, allowing them to interlock with the soil particles effectively.

5.4 Net Allowable Bearing Capacity

The allowable bearing capacity of the soil is determined based on the direct shear test results (Cohesion and friction angle) using the Terzaghi bearing capacity equation. Table 2 shows the percentage change in net allowable capacity values for different cases.

Table 2: Net Allowable Bearing Capacity

Soil Mixture Samples	Net Allowable Bearing Capacity (TSF)	ΔNABC (%)
Soil Alone	4.41	0%
RTC 0.25", 05% MIX	6.62	50.11%
RTC 0.25", 10% MIX	4.82	9.30%
RTC 0.25", 15% MIX	4.22	-4.99%
RTC 0.375", 05% MIX	5.02	13.41%
RTC 0.375", 10% MIX	4.02	-9.13%
RTC 0.375", 15% MIX	3.24	-26.32%
RTC 0.5", 05% MIX	3.65	-17.23%
RTC 0.5", 10% MIX	3.00	-32.01%
RTC 0.5", 15% MIX	2.49	-43.52%

Based on the above data, the mixture with RTC 0.25" and 05% content shows the highest improvement in Net Allowable Bearing Capacity (ΔNABC) by 50.11% compared to the "Soil Alone" mixture. Therefore, the RTC 0.25" and 05% mixture appears to be the best combination for improving the NABC value.

5.5 Design Thickness of Rigid Pavement

The thickness of Rigid Pavement was calculated using the procedure provided by AASHTO 93 guidelines. The percentage increases/decreases in thickness values for different cases are given table 3.

Table 3: Effect on Thickness of Rigid Pavement

Soil Mixture Samples	Thickness (inches)	Δ Thickness (%)
Soil Alone	9.99	0%
RTC 0.25", 05% MIX	9.75	-2.40%
RTC 0.25", 10% MIX	9.94	-0.50%
RTC 0.25", 15% MIX	10.01	0.20%
RTC 0.375", 05% MIX	9.92	-0.70%
RTC 0.375", 10% MIX	10.03	0.40%
RTC 0.375", 15% MIX	10.14	1.50%
RTC 0.5", 05% MIX	10.08	0.90%
RTC 0.5", 10% MIX	10.17	1.80%
RTC 0.5", 15% MIX	10.25	2.60%

Based on the above data, the mixture with RTC 0.25" and 05% content shows the highest reduction in thickness (Δ Thickness) by -2.40% compared to the "Soil Alone" mixture. Therefore, the RTC 0.25" and 05% mixture appears to be the best combination for decreasing the thickness value of the rigid pavement.

6. Conclusions

1. The unconfined compression test (UCS) revealed that the UCS values vary with different percentages and sizes of rubber tire chips. UCS values tend to decrease as the percentage of rubber tire chips increases. However, the 0.5-inch size at 5% showed the highest increase in UCS, indicating improved strength. This finding suggests that the 0.5-inch rubber tire chips at a 5% composition is the optimal mixture for overall stability and strength.
2. The California Bearing Ratio (CBR) values decreased as the thickness of the rubber tire chip (RTC) material increased. Additionally, the higher mixing percentages of RTC resulted in lower CBR values. Among the tested combinations, RTC, with a size of 0.25 inches at 5%, demonstrated the highest CBR value, indicating better soil strength in this mixture.
3. Mixtures with RTC 0.25" and 05% content show the highest improvement in friction angle and the lowest decrease in cohesion. That's why RTC 0.25" and 05% is the best combination for improving both internal friction and cohesion.
4. RTC 0.25" at 05% content yields the highest improvement in Net Allowable Bearing Capacity. RTC 0.25" and 05% are the best combination for enhancing bearing capacity.
5. RTC 0.25" at 05% content results in the highest reduction in pavement thickness, Which is why RTC 0.25" and 05% are the best combinations for decreasing pavement thickness.

7. Recommendations

1. The long-term performance assessment of pavements incorporating rubber tire chip additives requires extended studies over several decades to evaluate their durability and structural integrity.
2. Real-world monitoring is crucial for gaining practical insights into the longevity and effectiveness of these pavements.
3. Binder compatibility is another key area of focus, investigating interactions between rubber tire chips and various binders used in rigid pavements. This includes assessing how different binders affect the overall performance of rubber-modified pavements.
4. Additionally, transitioning from laboratory research to full-scale field testing is essential. Real-world applications must be evaluated to determine the actual performance of rubber-modified pavements under diverse traffic loads and environmental conditions, providing comprehensive and practical insights.
5. other factors like leaching risks, and economic feasibility should be studied in detail.

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